

Phenomenology of Light MSSM Higgs Boson Scenario

Alexander Belyaev^{1 ab}

School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, U.K.

Abstract. We have found that in the MSSM, the possibility for the lightest CP-even Higgs boson to be lighter than Z boson (as low as about 60 GeV) is, contrary to the usual belief, not yet excluded by LEP2 Higgs search nor any direct searches for supersymmetric particles at high energy colliders. The Light Higgs boson scenario (LHS) is realised when the ZZh coupling and the decay branching ratio $\text{Br}(h/A \rightarrow b\bar{b})$ are simultaneously suppressed as a result of generic supersymmetric loop corrections. Consequently, the $W^\pm H^\mp h$ coupling has to be large due to the sum rule of Higgs couplings to weak gauge bosons and as we demonstrate, the associate neutral and charged Higgs boson production process, $pp \rightarrow H^\pm h(A)$, at the LHC can completely probe the LHS.

PACS. 14.80.Cp Non-standard-model Higgs bosons – 12.60.Jv Supersymmetric models

While the Standard Model (SM) of particle physics is consistent with existing data, there is a strong belief in a more complete description of the underlying physics. Supersymmetry (SUSY), as a good candidate for theory beyond the SM, solves principal theoretical problems of the SM such as hierarchy and fine tuning, as well as provides good dark matter candidate and potentially solves the problem of baryogenesis. In the minimal supersymmetric standard model (MSSM) the Higgs sector consists of *two* doublet fields h_d and h_u to generate masses for down- and up-type fermions, respectively, and to provide an anomaly-free theory. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of charged Higgs bosons H^\pm , two neutral CP-even scalars H (heavier) and h (lighter), and a neutral CP-odd pseudoscalar A . Higgs potential is constrained by supersymmetry such that all the tree-level Higgs boson masses and self-couplings are determined by only two independent unknown parameters, commonly chosen to be the mass of the CP-odd pseudoscalar (M_A) and the ratio of vacuum expectation values of neutral Higgs fields, denoted as $\tan\beta \equiv \langle h_u \rangle / \langle h_d \rangle$.

The MSSM predicts a light neutral Higgs boson which is lighter than Z -boson at the tree level. However, large top quark and squark (stop) loop contributions induce significant radiative correction to the Higgs quartic coupling, such that the lighter neutral Higgs boson mass can be as large as 130 GeV [2, 3, 4, 5]. The negative result of Higgs boson search at LEP2 via $e^+e^- \rightarrow Zh$ production channel imposes a lower bound on the SM Higgs boson mass $M_h > 114$ GeV [6],

and excludes significant portion of MSSM parameter space.

The LEP2 collaborations have performed analyses for the MSSM [7] using several benchmark scenarios that were considered as typical cases for the MSSM parameter space. The two complementary processes for MSSM Higgs boson search are $e^+e^- \rightarrow Zh/Ah$ [7], in which the first one occurs via ZZh coupling $g_{ZZh} = \sin(\beta - \alpha) (\equiv s_{\beta\alpha})$ while the second one via ZAh coupling $g_{ZAh} = \cos(\beta - \alpha)$. The obvious sum rule ($g_{ZZh}^2 + g_{ZAh}^2 = 1$) puts strong constraints on the mass and couplings of the MSSM Higgs boson h . For all studied benchmark scenarios at LEP2, M_h below about 90 GeV is excluded [7].

In this study, we propose a different region of the MSSM parameter space which has not been previously studied with deserved attention. We call this possibility light Higgs boson scenario (LHS), in which the Higgs boson h is lighter than the Z -boson and the ZZh coupling is small enough to be consistent with the LEP2 data.

To satisfy the LEP2 constraint derived from the production channel $e^+e^- \rightarrow Zh$ with $M_h < M_Z$, the coupling g_{ZZh} (*i.e.* $s_{\beta\alpha}$) has to be small. Let us denote \mathcal{M}^2 as the 2×2 squared-mass matrix of the CP-even neutral Higgs bosons in the gauge eigenbasis ($\text{Re } h_d^0, \text{Re } h_u^0$). The mass eigenstates (h, H) are given by the diagonalization of the matrix \mathcal{M}^2 with the definition:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -s_\alpha & c_\alpha \\ c_\alpha & s_\alpha \end{pmatrix} \begin{pmatrix} \text{Re } h_d^0 \\ \text{Re } h_u^0 \end{pmatrix}, \quad (1)$$

where $c_\alpha \equiv \cos \alpha$ and $s_\alpha \equiv \sin \alpha$ (with $-\pi/2 \leq \alpha \leq \pi/2$).

Denote $x \equiv \mathcal{M}_{11}^2 - \mathcal{M}_{22}^2$ and $y \equiv \mathcal{M}_{12}^2$, in terms of the components of matrix \mathcal{M}_{ij}^2 . For relatively large

^a Email: a.belyaev@soton.ac.uk

^b the study has been done in collaboration with Qing-Hong Cao, Daisuke Nomura, Kazuhiro Tobe and C.-P. Yuan [1]

$\tan\beta$	M_{H^+}	μ	A_3	$M_1 = M_2/2$	M_3	M_Q
35	135	890	750	100	600	330
$M_h = 71, M_A = 113, M_H = 119$ $\text{Br}(h/A/H \rightarrow b\bar{b}) = 0.65/0.64/0.03$ $\text{Br}(h/A/H \rightarrow \tau\bar{\tau}) = 0.25/0.34/0.54$ $g_{ZZh}^2 = 0.006, g_{ZZH}^2 = g_{H^+W^-h}^2 = 0.994$ $M_{\tilde{\chi}_1^0} = 100, M_{\tilde{\chi}_1^+} = 198, M_{\tilde{t}_1} = 126, M_{\tilde{b}_1} = 273$ $\Delta\rho = 6.7 \times 10^{-4}$						

Table 1. The MSSM parameters (at the weak scale) of an LHS sample point. The dimension of mass parameters is in unit of GeV. $M_i (i = 1, \dots, 3)$, M_Q and A_3 are gaugino masses, the universal soft-breaking sfermion mass and universal trilinear A-term for the third-generation at the weak scale, respectively. $M_{\tilde{\chi}_1^+}$, $M_{\tilde{t}_1}$ and $M_{\tilde{b}_1}$ are pole masses for the lightest chargino, stop and sbottom, respectively.

$\tan\beta$ (as preferred by the LHS) and $y/x \simeq 0$, we find $s_{\beta\alpha} \simeq \frac{(|x|+x)^{1/2}}{\sqrt{2|x|}}$ which vanishes for $x < 0$. Therefore, conditions $y/x \simeq 0$ and $x < 0$ provide small values of $s_{\beta\alpha}$. The light Higgs boson h mainly consists of h_d^0 , and the neutral Higgs boson masses are approximately given by $M_h^2 \simeq M_{11}^2$ and $M_H^2 \simeq M_{22}^2$. This feature is different from the usual scenarios in which $M_h^2 \simeq M_{22}^2$ and $M_H^2 \simeq M_{11}^2$. As it is well-known, M_{22}^2 (i.e. h_u -component) receives large positive logarithmic correction from top and stop contributions. This correction, which helps to significantly increase the mass of h in the usual scenarios, increases the mass of H in the LHS and changes the sign of x value from positive (at tree level) to negative when $M_A \sim M_Z$. The condition $y/x \sim 0$ (needed for the LHS) can only be satisfied in some regions of MSSM parameter space which is studied below.

As an illustration, we present in Table 1 one LHS sample point where the gaugino masses (with $M_2 = 2M_1$), the supersymmetric Higgs mass μ -parameter (μ), the universal soft-breaking sfermion mass (M_Q), and the trilinear A-term (A_3) for the third-generation at the weak scale are all at (or below) TeV scale. For our numerical analysis, we use CPsuperH program [8] and assume CP is conserved. For the LHS sample point specified in Table I, $x > 0$, $y/x \simeq -0.2$ and $s_{\beta\alpha} \simeq 0.98$ at tree level. After including radiative corrections, the Higgs mass matrix elements in the effective potential become $M_{11}^2 \simeq (71.0 \text{ GeV})^2$, $M_{22}^2 \simeq (119.7 \text{ GeV})^2$, and $M_{12}^2 \simeq -(19.5 \text{ GeV})^2$, hence, $x < 0$ and $y/x \simeq 0.041$. (The mass of top quark is taken to be 172.5 GeV.) Consequently, we obtain a small $s_{\beta\alpha}$ ($\simeq 0.069$). Note that in the LHS, the lighter Higgs boson mass is close to its tree-level value $M_h \simeq \sqrt{M_{11}^2} \sim M_Z$ when $M_A \sim M_Z$. This feature is qualitatively very different from the commonly discussed MSSM scenarios in which M_h receives large radiative corrections. Moreover, the mass of the heavier CP-even Higgs boson H must receive large radiative corrections to exceed about 114 GeV in order to agree with LEP2 data, since the ZZH coupling is close to the SM value.

To find the allowed parameter space for the LHS with $\mu > 0$, we scan the following set of MSSM parameters: $\tan\beta$ [1.1, 50], (M_{H^+}/TeV) [0.1, 0.2], (A_3/TeV) [-2, 2], (M_1/TeV) [0.05, 1], (M_3/TeV) [0.05, 1], (M_Q/TeV)

[0.05, 1] and (μ/TeV) [0, $3M_Q$], within the range denoted in brackets. Since a too large μ -parameter induces not only the color breaking vacuum in the general direction of the scalar potential but also the fine-tuning in the Higgs mass parameter, we require μ to be less than $3M_Q$ in our analysis [9,10]. Then, we check the LHS parameter space against the full set of the experimental and theoretical constraints. They are: (1) LEP2 Zh/ZH and Ah/AH constraints, cf. Tables 14 and 17 of Ref. [7]; (2) Chargino ($M_{\tilde{\chi}_1^+}$), stop ($M_{\tilde{t}_1}$), sbottom ($M_{\tilde{b}_1}$) and gluino (M_3) mass limits: $M_{\tilde{\chi}_1^+} > 103 \text{ GeV}$ [11], $M_{\tilde{t}_1} > 96 \text{ GeV}$ [11], $M_{\tilde{b}_1} > 220 \text{ GeV}$ for $M_{\tilde{\chi}_1^0} < 90 \text{ GeV}$ and $M_{\tilde{b}_1} - M_{\tilde{\chi}_1^0} > 6 \text{ GeV}$ (where $M_{\tilde{\chi}_1^0}$ is the lightest neutralino mass) [12] or $M_{\tilde{b}_1} > 100 \text{ GeV}$ for all other regions [11], and $M_3 > 270 \text{ GeV}$ for $M_{\tilde{b}_1} < 220 \text{ GeV}$ and $M_3 - M_{\tilde{b}_1} > 6 \text{ GeV}$ [13] or $M_3 > 240 \text{ GeV}$ for all other regions [14]; (3) electroweak constraint: one-loop stop contributions to ρ -parameter $|\Delta\rho_{\text{stop}}| < 2 \times 10^{-3}$ [15]; (4) color breaking constraint: $A_3^2 < 3(2M_Q^2 + M_{h_u}^2 + \mu^2)$ where M_{h_u} is the soft-breaking mass for Higgs h_u [9,10].

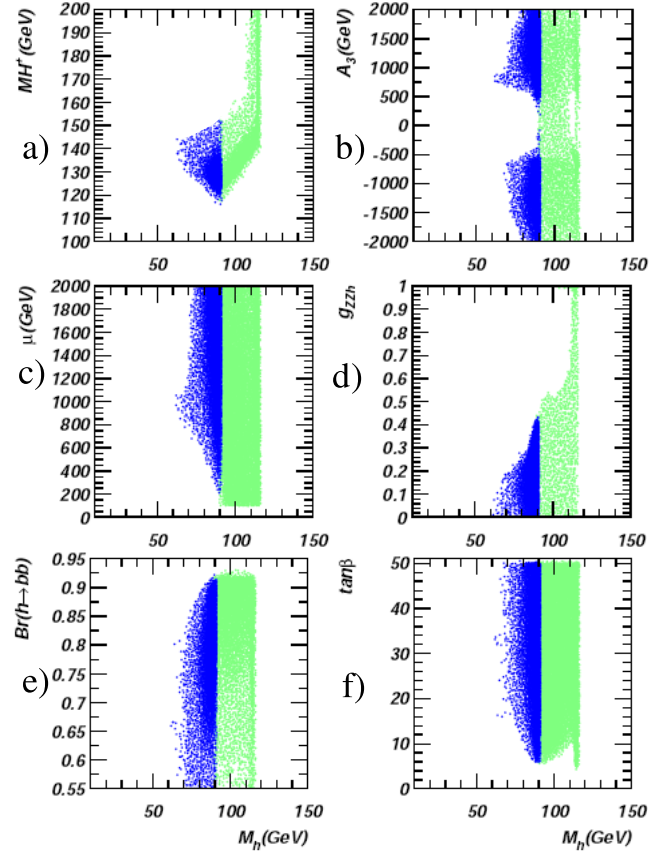


Fig. 1. Projected planes of scanned parameter space indicating the LHS region in accord with experimental data. (See detail explanation in the text.)

Our result is shown in Fig. 1 where blue (darker) and green (lighter) color indicates allowed parameter space with $M_h < M_Z$ and $M_h > M_Z$, respectively.

Fig. 1a (M_{H^+} - M_h plane) shows that LHS scenario is realized for low values of charged Higgs boson mass: $120 \text{ GeV} < M_{H^+} < 150 \text{ GeV}$, indicating the non-

decoupling regime. Much lighter charged Higgses are excluded mainly by the LEP2 Higgs search via the Ah production channel. The scenario requires intermediate-to-large values of the A-term and μ -parameter, $|A_3| > 400$ GeV and $\mu \gtrsim 300$ GeV (cf. Figs. 1b and c) to make g_{ZZh} small, as indicated in Fig. 1d. On the other hand, a larger *positive* value of the product $M_3\mu \tan\beta$ gives rise to larger *negative* correction to the bottom Yukawa coupling y_{hbb} . This large negative correction to y_{hbb} is *non-universal* with respect to the τ Yukawa coupling $y_{h\tau\tau}$ and leads to a suppression in $\text{Br}(h/A \rightarrow b\bar{b})$ [16] large enough to avoid LEP2 constraint from the Ah channel with low M_h values. In the LHS parameter space, $\text{Br}(h/A \rightarrow b\bar{b})$ can be suppressed down to about 50% (cf. Fig. 1e), and consequently $\text{Br}(h/A \rightarrow \tau\bar{\tau})$ is enhanced up to about 50%, so that Ah channel is not observed: $b\bar{b}b\bar{b}$ decay mode is largely suppressed, while $b\bar{b}\tau\bar{\tau}$ or $\tau\bar{\tau}\tau\bar{\tau}$ signatures are not enhanced enough to exclude $60 \text{ GeV} \lesssim M_h < M_Z$. Fig. 1e presents the $\text{Br}(h \rightarrow b\bar{b})$ - M_h correlations. It is interesting to note that the relatively large μ -parameter simultaneously suppress both $s_{\beta\alpha}$ and $\text{Br}(h/A \rightarrow b\bar{b})$ to be consistent with the LEP2 data. We also note that a lighter Higgs boson is preferred for a larger $\tan\beta$ value, cf. Fig. 1f. It is worth mentioning that although the heavier Higgs boson (H) couplings to vector bosons are SM-like, its couplings to down-type fermions are further suppressed as compared to those of h and A (cf. Table 1). Moreover, M_A ranges from 90 to 120 GeV, which can be well approximated by $M_A = \sqrt{M_{H^+}^2 - M_W^2}$.

Since in the LHS, $g_{ZZh} (= s_{\beta\alpha})$ is suppressed, H^+W^-h coupling is inevitably enhanced due to the sum rules in Higgs boson couplings to weak gauge bosons, i.e., $g_{ZZh}^2 + g_{H^+W^-h}^2 = 1 = g_{H^+W^-A}^2$. In this case the $q\bar{q}' \rightarrow H^\pm h(A)$ production via W boson exchange could be sizable with the production cross section ~ 10 fb at the Tevatron and ~ 100 fb at the LHC for $M_{h/A} \sim 100$ GeV [17,18]. In Fig. 2 we present the inclusive cross

section of the $p\bar{p}, pp \rightarrow H^+h(A) \rightarrow \tau^+\nu b\bar{b} \rightarrow \pi^+\bar{\nu}\nu b\bar{b}$ signature at the Tevatron and the LHC in the M_{H^\pm} - M_h plane. For simplicity, we have combined the H^+h and H^+A production rates. (We note that the tree level production rate of H^+A pair in the MSSM is independent of $\tan\beta$.)

As clearly shown in Fig. 2, the LHC can be sensitive to the entire LHS parameter space, assuming that the above signal event signature can be measured at the 1 fb level [18]. The potential of the Tevatron to observe the H^+A/H^+h production processes deserves special investigation and will be reported elsewhere [19]. We also note that when $s_{\beta\alpha}$ is small, the tree level bottom and τ Yukawa couplings are enhanced by a factor of $(-\sin\alpha/\cos\beta) \simeq \tan\beta$, compared with the SM values. Therefore, the LHS, which is realized in intermediate-to-high $\tan\beta$ region, can be potentially probed even at the Tevatron via several $\tan\beta$ -enhanced processes, such as $p\bar{p} \rightarrow h(A)$ (produced via gluon-gluon fusion process) with $h/A \rightarrow \tau\bar{\tau}$, $p\bar{p} \rightarrow b\bar{b}h(A)$, as well as $p\bar{p} \rightarrow t\bar{t}$ with $t \rightarrow H^+b$. At present luminosity, those processes are sensitive only to very large values of $\tan\beta \gtrsim 45 - 50$, while at 10 fb^{-1} , $\tan\beta \gtrsim 30$ could be probed [20,21]. At the LHC, a smaller $\tan\beta$ value ($\gtrsim 10$) of the LHS can be tested via the $\tan\beta$ -enhanced processes, such as $pp \rightarrow (h, H, A) \rightarrow \tau\bar{\tau}$ [22]. Furthermore, given the expected large number ($\sim 10^8$) of top quark pairs produced at the LHC, the LHS can manifest itself in the copious $t \rightarrow H^+b$ decays as long as M_{H^+} is not too large (below about 140 GeV) [23].

Conclusions: We have shown that in the MSSM the possibility for the CP-even Higgs boson h to be lighter than Z -boson (as low as about 60 GeV) is, contrary to the usual belief, not yet excluded by the existing direct search experiments. The characteristic of the light Higgs boson scenario (LHS) is that the ZZh coupling and the decay branching ratio $\text{Br}(h/A \rightarrow b\bar{b})$ are simultaneously suppressed as a result of SUSY loop corrections. We would also note that the region of MSSM parameter space considered for explaining the non-conclusive LEP2 excess of the ~ 98 GeV 'Higgs-like' events [6], as studied in the literature (see, e.g., [24, 25]), is a subset of the more generic LHS parameter space that we have found in this paper. Our result would be useful for clarifying the parameter space responsible for this excess.

The implications of the LHS to the usual LHC (and Tevatron) search strategies for the lighter CP-even Higgs boson (h) can be summarized as follows. In view of its production mechanisms, both the vector boson fusion process and the associated production of h with vector boson are largely suppressed, while the associated production of h and H^+ is enhanced by the large W - h - H^+ coupling. In view of its decay channels, the decay branching ratio of h into $b\bar{b}$ mode is reduced and the $\tau^+\tau^-$ mode is enhanced. Also, as compared to the SM rates, the $gg \rightarrow h \rightarrow \gamma\gamma$ rate is reduced by a couple of orders of magnitudes and the $gg \rightarrow h \rightarrow \tau^+\tau^-$ rate is enhanced by about an order of magnitude for h around 60 GeV. Since the mass of

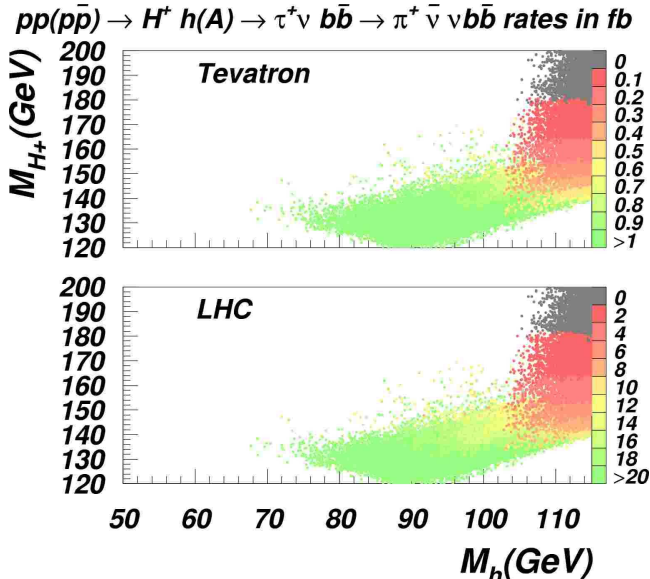


Fig. 2. Rates for $p\bar{p}, pp \rightarrow H^\pm h(A) \rightarrow \tau^\pm \nu b\bar{b} \rightarrow \pi^\pm \bar{\nu} \nu b\bar{b}$ signature at the Tevatron and the LHC.

the heavier CP-even Higgs boson is below 130 GeV in the LHS, there is no resonance enhanced hh pair production from gg fusion process. The only large Higgs pair production rate at the LHC is via $pp \rightarrow H^\pm h(A)$ whose production cross sections are sizable (above a few hundreds fb) and insensitive to the value of $\tan\beta$. (The tree level AH^\pm rate is independent of $\tan\beta$.) Hence, if this production channel is not observed at the LHC, it would undoubtedly exclude the LHS. On the other hand, if this production channel is detected, a large production rate of the heavier Higgs boson H via vector boson fusion process is expected in the LHS.

Finally, we note that in the LHS, B physics processes at B -factories, Tevatron and LHC, such as $b \rightarrow s\gamma$, $B^- \rightarrow \tau^- \bar{\nu}$, $B_{d,s} \rightarrow \mu^+ \mu^-$ and $B_s - \bar{B}_s$ oscillation measurements, could be largely modified due to the sizable contributions from light (neutral and charged) Higgs bosons. Since the predictions on those processes could strongly depend on the flavor structure of the SUSY breaking parameters, we do not impose any constraints from flavor physics to further restrict the allowed MSSM parameter space of the LHS presented in this work. A detailed study of the constraints from flavor physics, under a specific assumption of the flavor structure, is interesting and deserves a separate study.

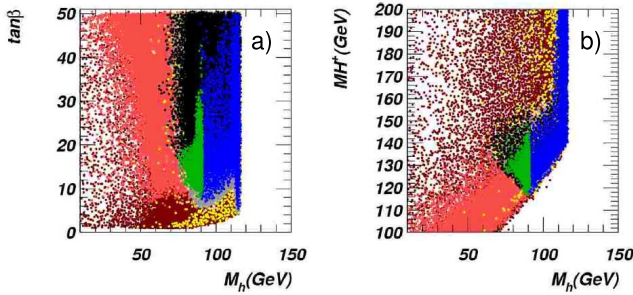


Fig. 3. The allowed LHS parameter space (green area) after application constraints from B -physics (black and gray areas) combined with LEP2 constraints (red, dark red and yellow areas).

Our preliminary study [19] shows that even for the commonly discussed minimal-flavor-violation (MFV) scenario in which flavor violation is solely generated by SM Cabibbo-Kobayashi-Maskawa (CKM) matrix, the LHS can be consistent with all the present B -physics data though its parameter space is largely reduced. In Fig. 3 we present the allowed LHS parameter space indicated by green area after application B -physics constraints (black and gray areas) combined with LEP2 constraints (red, dark red and yellow areas). The blue color indicates the allowed parameter space for $m_h > M_Z$. All other colors indicate the excluded regions. One can see that m_h is required to be larger than about 80 GeV while $\tan\beta$ is bounded to be less than about 20, mainly due to the $B_{d,s} \rightarrow \mu^+ \mu^-$ constraint represented by black area. Hence, it is expected that the MSSM LHS would require a non-MFV flavor sector, should h boson be much lighter than Z boson. Its detail will be published in a forthcoming paper [19].

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